Studies in History and Philosophy of Modern Physics 63 (2018) 141–149

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Issues in the theoretical foundations of climate science

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ARTICLE INFO

Article history:
Received 28 September 2017
Received in revised form
7 February 2018
Accepted 12 February 2018
Available online 7 March 2018

Keywords:
Philosophy of climate science
Theoretical foundations of climate science
Theoretical foundations of science
Climate science
Climate states
Climate sensitivity

ABSTRACT

The theoretical foundations of climate science have received little attention from philosophers thus far, despite a number of outstanding issues. We provide a brief, non-technical overview of several of these issues – related to theorizing about climates, climate change, internal variability and more – and attempt to make preliminary progress in addressing some of them. In doing so, we hope to open a new thread of discussion in the emerging area of philosophy of climate science, focused on theoretical foundations.

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1. Introduction

Philosophers of science have become increasingly interested in climate change and climate science. Thus far, attention has focused primarily on the epistemology of climate science, especially climate modelling. Philosophers have analysed how climate models are constructed and evaluated, and they have debated how uncertainties associated with model-based projections of climate change should be characterized (e.g., Parker, 2009 , 2010b; Lloyd, 2010; Katzav, 2014; Katzav, Dijkstra, & de Laat, 2012; Betz, 2015; Frigg, Thompson, & Werndl, 2015). They have also investigated conflicts between climate models and observational data (e.g. Lloyd, 2012), how non-epistemic values might influence climate model projections (Intemann, 2015; Parker, 2014; Winsberg, 2012) as well as how various sources of evidence for climate change are amalgamated and synthesized (e.g. Katzav, 2013; Vezér, 2016).

The theoretical foundations of climate science, by contrast, have received very little attention from philosophers (the sole exceptions, as far as we can tell, are Werndl (2016) and Lawhead (forthcoming)). However, these foundations merit scrutiny and development just as do those of biology, chemistry and physics. This includes theorizing about climate states, climate change, climate sensitivity, radiative forcing, and more. Indeed, climate scientists themselves recognize the need for work on the theoretical foundations of their discipline. Thus, for example, Lovejoy and Schertzer (2013, p. 337), argue that the standard ways of characterizing climate states are not sufficiently objective. Ghil (2015) and von der Heydt et al. (2016) argue that available ways of thinking about climate sensitivity are not sufficiently general. The U.S. National Research Council (USNRC, 2005, p. viii) makes a similar point, but about the standard notion of radiative forcing (cf. Sherwood et al., 2015).

The present paper aims to provide philosophers interested in climate science with a brief, non-technical overview of these and several other key issues in the theoretical foundations of contemporary climate science. We focus our attention on the notions of climate system, climate state, climate change, climate sensitivity, internal variability and radiative forcing. Addressing in detail any one of the issues that we identify would be a major undertaking in itself; here our main aim is rather to give a sense of what some of the key issues are and of how they are related to one another. In other words, our aim in this paper is more agenda-setting than problem-solving. We do, however, offer some preliminary suggestions for ways of tackling some issues as well as an indication of how doing so relatively systematically might be advantageous.

Our discussion aims to be responsive to foundational issues that climate scientists encounter in their research and, accordingly,

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https://doi.org/10.1016/j.shpsb.2018.02.001
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primarily focuses on pragmatic issues; such issues arise because available notions are, in one way or another, less than optimal for realizing the inferential and explanatory goals of climate science. Thus, the issues we identify largely concern the usefulness of specific notions for the purposes of interpreting and explaining observations of the climate system, developing and using climate models for predictive and other purposes, and drawing conclusions about the behaviour of the climate system in one period from its behaviour in another – e.g., using palaeo-data to inform conclusions about future climate change. Importantly, we will see that it is a challenge to develop notions of climate states and climate sensitivity that are general enough to accommodate what we know about the climate system and, at the same time, sufficiently informative about physical aspects of climate to guide inference and explanation in climate science. We will also see that the current focus on reductive notions of climate states and climate systems might be less than optimal, given the goals of explaining and predicting climate.

Alongside pragmatic issues, we present issues that may have a pragmatic dimension but that appear primarily to be conceptual. The conceptual issues include tensions within ways of thinking about the boundary of the climate system as well as a lack of clarity about what exactly should count as internal variability and what should count as external variability.

Our discussion proceeds as follows. In Section 2, we focus on issues that arise when trying to characterize Earth's *climate system*. We discuss the challenge of identifying the boundaries of the system and consider whether the climate system should be characterized in a wholly reductive way, i.e., solely in terms of material constituents and their causal interactions. Section 3 is concerned with theorizing about *climate states*. We consider the limitations of the standard statistical approach to characterizing climate states, and we argue for the benefits of a proposed alternative approach, which contends that climate states should be characterized in part in physical terms. The issue of reductionism resurfaces in this section as well, as we examine the suggestion that climate states can be characterized in part in terms of emergent properties.

Section 4 focuses on *climate change* and the closely related notion of *climate sensitivity*. We note that it is an open question which aspects of the climate system should be appealed to in characterizing climate change, though very often the focus is on changes in global mean near-surface air temperature. It is this change that is the focus, for instance, in standard analyses of the sensitivity of the climate system to external forcing. We also explain why (as noted above) this standard notion of climate sensitivity is insufficiently general – the fact that it is focused on equilibrium conditions is only part of the problem – and consider the challenges that remain for some alternative, more general notions that have been developed.

Section 5 is concerned with *internal variability* and *radiative forcing*. We note that internal variability is sometimes assumed to be a separable, independent component of total climate variability; this, we argue, does not seem to take into account the very plausible situation in which external forcing is changing the magnitude and frequency of climate system phenomena that are commonly taken to be expressions of internal variability, such as El Nino. With regard to radiative forcing, we explain why a more general notion of forcing seems to be required, highlighting connections with issues raised for the notions of climate system and climate sensitivity. Indeed, throughout the paper, we call attention to interconnections among the issues discussed.

Finally, in Section 6, we offer a concluding discussion. We review the issues that we have identified along the way, note some of the progress that has been made in addressing them, and suggest, partly on the basis of the work done here, that there is room for philosophers of science to contribute to addressing issues in the theoretical foundations of climate science. We close with some remarks on the importance of doing so.

2. Climate system

All of the issues we will examine concern climate systems or their features – their states, components, evolution and responses to external influences. A natural place to start our investigation is thus with the standard notion of Earth's climate system. The Intergovernmental Panel on Climate Change provides what is, minor variations aside, the standard notion of Earth's climate system:

> **Climate system.** The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change [IPCC, 2014, p. 121].

Here, the climate system is characterized in terms of its material components, especially a set of subsystems, and their causal interactions. Two issues that arise in connection with the standard notion are where to draw the boundary of our climate system and whether the system should be characterized in a wholly reductive way. We look at each of these issues in turn.

The standard notion specifies the boundary of the climate system in terms of the spatial boundaries of the system's components and, in doing so, makes clear that some factors, e.g., changes in solar irradiance, are external to our climate system. Yet, as climate scientists are well aware, it is not obvious that changes in volcanic aerosol concentrations, anthropogenic land-use changes or anthropogenic increases in CO_2 concentrations should be considered external. After all, these are changes in the biosphere or the atmosphere and thus seem to be, according to the standard notion, *within* our climate system.

An alternative suggestion that climate scientists sometimes make is that something counts as external to Earth's climate system on a given timescale if it is causally independent of changes in the system on that timescale (USNRC, 2005, p. 14). This would imply that volcanic aerosol concentration changes are external to the climate system on century timescales, because changes in the Earth's climate system do not impact volcanic activity except on much longer timescales. It is not clear, however, that this approach successfully renders 'external' other elements that are usually so classified in practice. For example, anthropogenic CO_2 concentrations over the 20th and 21st centuries may well depend (via human intentions and actions) on their effects during this period; efforts have already been made to reduce emissions, for instance, in light of occurring and anticipated harmful consequences of increased emissions. Further, the suggestion appears to be circular as it explicates being external to Earth's climate system in terms of what can affect the system in a certain way.

This circularity could be avoided by refining the characterization slightly, such that something counts as being external to the climate system if it is causally independent of changes in paradigmatic climate variables (e.g., temperature and precipitation) on that timescale. A definition modified along these lines, however, would require a non-circular specification of which variables count as paradigmatic climate variables, would raise the issue of why certain variables and not others are selected, and would still seem to imply

that anthropogenic CO_2 concentrations over the 20th and 21st centuries are 'internal' to the climate system, for the same reason given above. Nevertheless, a significant advantage of such 'causal independence' approaches is that they provide direct guidance for modelling practice: whether some quantity is causally independent of key climate variables over timescales of interest is a useful guide to whether that quantity can be stipulated in climate models, without adversely affecting the accuracy of their simulations with respect to those key variables.[1]

By contrast, no such guidance is provided by an alternative 'pragmatic' approach, which draws the boundaries of the climate system with reference to climate models. On the pragmatic approach, a quantity is external to the climate system if it is modelled as exogenous, that is, if its values are stipulated during model runs regardless of how other model variables evolve (see, e.g., Schmidt, Shindell, Miller, Mann, & Rind, 2004). Moreover, what counts as Earth's climate system is model-relative on this approach, since in practice which quantities are stipulated varies across existing climate models. Nevertheless, the pragmatic approach does fit with the common practice of classifying anthropogenic changes in CO_2 concentrations and land use as "external forcings": these changes have traditionally been, and often still are (Collins et al., 2013, p. 1052), represented as exogenous variables in today's models, though they are not causally independent of changes in temperature and other climate variables.

Perhaps then the standard characterization of Earth's climate system given at the start of this section can be understood as a sort of compromise: the climate system is defined spatially, but some factors that are within those spatial boundaries are declared to be external, either because they are difficult to model interactively (e.g. anthropogenic CO_2 concentrations) or because there is no need to model them interactively on time scales of current interest (e.g. volcanic eruptions). Such a compromise comes at a cost. Most obviously, there is a kind of internal tension (or even outright inconsistency) in the characterization as stated. Less obviously, but perhaps more importantly, the characterization obscures the fact that, for some time scales, if accurate predictions of climate-related quantities of interest are desired, it may be necessary to model some of these "external" factors (such as anthropogenic CO_2 concentrations) interactively. It remains to be seen, however, what a better characterization of the climate system might look like, and the extent to which the practical constraints faced in climate modelling should play a role in its development.

A second issue is whether Earth's climate system should be conceptualized in a partly non-reductive way. A partly non-reductive conceptualization would represent the system in terms of some emergent laws (or regularities) and properties, that is, laws and properties that characterize it as a whole but need not characterize its material constituents. Moreover, the non-reductive characterization would treat the system's emergent laws and properties as basic rather than deriving them or explaining them by appealing to its constituents and their governing laws. A reductive conceptualization, by contrast, represents the system only in terms of its material constituents and their governing laws or relationships.

The IPCC definition given above includes no non-reductive elements. It identifies the climate system solely as an entity with a certain composition. This definition meshes well with the standard approach to climate modelling, which aims to develop models that explicitly represent ever smaller temporal and spatial-scale phenomena within the climate system; ideally, for example, state-of-the-art models of the climate system would explicitly represent the formation and evolution of individual clouds. Such an approach is motivated by the belief that explicit representation of small-scale physical processes will improve simulations of climate phenomena of interest, including climate change.

Some non-reductive characterisations of the climate system have been offered, however, with corresponding non-standard approaches to modelling it. For instance, Hasselmann (1976) proposes that we think of the climate system as comprising two types of processes, namely, fast weather processes and slow climate processes. This allows modelling the climate system using an equation that explicitly represents only slow climate processes; the effects of the fast weather processes on the slow processes are represented by a stochastic term in the equation, and the fast processes themselves are not explicitly represented (See Franzke, O'Kane, Berner, Williams, & Lucarini, 2015 for a survey of the various ways in which Hasselmann's ideas have been developed.)

Another proposal is that the climate system can be thought of as a type of system that operates out of thermodynamic equilibrium and is subject to a thermodynamic extremum principle that constrains how its entropy evolves. Specifically, it has been proposed that (MEP) our climate system is a system that evolves so as to maximize entropy production (Paltridge, 1978 & 1979; Ozawa, Ohmura, Lorenz, & Pujol, 2003; Dewar, Lineweaver, Niven, & Regenauer-Lieb, 2014). In the original application of this idea, heat transport in the atmosphere was modelled so that it adjusts so as to maximize the production of the atmosphere's entropy (Paltridge, 1978). More recent applications include, among others, simulating the climate state of the Last Glacial Maximum (Herbert, Paillard, Kageyama, & Dubrulle, 2011). While some have suggested that MEP is a law governing climate systems, others have disputed this. The issue is an open one (Dewar et al., 2014; Ozawa et al., 2003).

As the examples cited above suggest, incorporating non-reductive elements in a characterization of Earth's climate system could matter in practice, because doing so might affect how climate is modelled. Indeed, it is plausible that further developing and evaluating non-reductive characterizations in order to guide modelling practice would be of value (cf. Harrison and Stainforth 2009). It may be useful to consider, for instance, the extent to which it is accurate and helpful to think of the climate system as a kind of heat engine, as the framework underlying MEP supposes. Models which implement non-reductive, global constraints on climate evolution, such as MEP, could complement the increasingly complex causal modelling that is the current focus of climate modelling. Increased computational efficiency aside, an advantage of such top-down modelling approaches is that they can guarantee that emergent properties of the climate system, to the extent that these are known, are captured by available models.[2] Even when the evidence for an emergent property is only suggestive, it would seem desirable to develop some climate models that reflect that property. This will help to ensure that the discipline is working with a set of models that reflects actual uncertainty about the nature of the climate system. Developing non-reductive climate models, as well as the frameworks that guide the development of such models, may also contribute to a better understanding of climate phenomena; as Katzav and Parker (2015) note, just as global conservation principles can provide an understanding of some climatic

[1] Lawhead (forthcoming) also notes the connection between which quantities a model represents as part of the climate system and the usefulness of the model's predictions.

[2] When such properties are not explicitly built into models, it could turn out that they do not in fact emerge in the simulation, given the way 'lower level' processes and entities are represented.

phenomena, so too might principles that reference emergent properties and relationships.

Finally, one might think that a characterization of Earth's climate system could be guided by a more general notion of a climate system that applies to other planets as well. Such a notion, however, does not seem to have been developed, either in climate science (which tends to focus on Earth in particular) or in fields like planetary science, despite discussion of general features of planetary climate systems (e.g. Ozawa et al., 2003; Schubert & Mitchell, 2013). Moreover, on reflection, it seems likely that formulating a general notion of a climate system will involve the same two issues identified above – whether to be reductive and how to characterize boundaries. Indeed, giving a characterization of climate system boundaries in general may be more challenging than specifying the boundaries of Earth's climate system since, in the general case, we cannot assume a fixed list of 'component' systems.

3. Climate states

The IPCC distinguishes between a narrow notion of climate and a broad one (IPCC, 2014, pp. 119–120). According to the narrow notion, climate is the statistical distribution of weather for a region over a period of time ranging from months to millions of years; the standard period of time is 30 years. The broader notion of climate considers not just weather conditions but conditions throughout the climate system (i.e., its full state, including conditions in the ocean, cryosphere, etc.). In some contexts, a dynamical systems perspective on climate is adopted, and climate is then identified with an attractor of a climate system (see, e.g., Palmer, 1999, von der Heydt & Ashwin, 2016, Werndl, 2016). 'Climate' is often shorthand for 'climate state' or 'climate regime'.

A central question that arises in connection with the notion of climate is which actual, long-term (decadal and longer) distributions should be those that characterize climate states; from a dynamical systems perspective, the question is which, if any, are distributions that characterize attractors of the system. Distributions of climate variables obviously change with the time-scale considered. Discussions of which distributions to prefer often emphasize statistical and pragmatic considerations, such as the fact that observations indicate that, for at least some periods in Earth's history, the mean of variables such as temperature tends to converge once periods reach a length of about 30 years (see Lovejoy & Schertzer, 2013, p. 341; see also, e.g.,; Arguez & Vose, 2011; Werndl, 2016).

Lovejoy and Schertzer (2013), however, have argued that statistical characterizations ultimately are inadequate. On their view, the notion of a climate state, and by implication characterisations of particular states of this kind, should be statistical *and physical*; they should reference physical drivers of climate variability, e.g., deep ocean currents and the solar energy flux. This should be the case, the claim is, because statistical characterizations do not provide justification for settling on one or another period of time for estimating a climate; the choice of time period is insufficiently objective on their view (2013, pp. 337-338). Lovejoy and Schertzer are not explicit, however, about why justification is needed here. Nor do they explain why justification might only be provided via physical considerations rather than, say, in light of practical goals. One might, for example, try to justify using the standard 30-year period for determining climate states on the ground that such relatively short timescales are policy relevant.

Nevertheless, there are some advantages to enriching the characterization of climate states using physical information. First, doing so may contribute to our understanding of the statistical characteristics of climate states, e.g., by helping to explain why mean temperature is highly variable over short (up to decadal) timescales but exhibits identifiable trends over longer timescales. Second, climate states that have very similar distributions of weather conditions but quite different underlying physical processes driving those conditions will evolve differently into the future; thus, the enriched characterization may provide a better basis for predicting the evolution of climate states.

There are already indications of how this enrichment of the characterizations of climate states might be approached in practice. Lovejoy and Schertzer (2013) draw upon theoretical resources as well as paleo-data analysis. One of the main conclusions of their analysis is that we cannot fully define a climate state by appealing to a single temporal scale; different scales, on their view, will reflect different aspects of the underlying physics of a climate state. Enriching the characterization of climate states can also be undertaken with the help of climate models. For example, climate models are already being used to characterize how distributions of climatic quantities on interannual and decadal timescales depend on underlying physical processes (Daron & Stainforth, 2013; Hawkins, Smith, Gregory, & Stainforth, 2016; Sévellec et al., 2017).

A second issue, also raised by Lovejoy and Schertzer, concerns whether the notion of climate should be reductive. They argue that the standard notion, along with the standard development of state-of-the-art climate models, assumes that the dynamics of climate is reducible to that of weather, that is, that it is just the dynamics of weather on relatively long timescales. This, they write, "seems naïve, since we know from numerous examples in physics that when processes repeat over wide enough ranges of space or time scale they typically display qualitatively new features" (Lovejoy & Schertzer, 2013, p. 338). An alternative, they propose, is that the behaviour of climate is appropriately described by emergent laws that differ qualitatively from the laws of weather. Indeed, they, and others, provide a range of empirical evidence that suggests that climate does exhibit emergent regularities (See, for example, Huybers & Curry, 2006, Lovejoy & Schertzer, 2013, Lovejoy, 2015, Rypdal & Rypdal, 2016.)

There is much to consider here. Is thinking of climate states in terms of distributions of weather conditions indeed so intimately tied to a view about the dynamics of climate? Perhaps one can accept the standard way of thinking but still allow for an emergent climate dynamics. There is also the question whether processes that are 'regular enough' should be expected to give rise to qualitatively new emergent features and, if they do, whether these will involve corresponding emergent *laws* or other emergent, but more local, relationships. In addition, note the parallel between this non-reductive approach to characterizing climate states and the suggestion, in the previous section, of the potential benefits of taking account of emergent laws and properties of the climate system when constructing climate models. In the case of climate states, it has been argued that taking account of emergent regularities may facilitate climate prediction (see, e.g., Lovejoy, 2014). Thus, just as taking account of emergent laws and properties of the climate system might aid in learning about climate phenomena, so too might taking account of emergent properties of climate states.

Werndl (2016) suggests that whether the characterization of climate states should be done using finite or infinite distributions is also an issue that needs to be addressed. She notes that, since the external conditions affecting climate are time-dependent, there is no guarantee that a given climatic quantity will have a well-defined distribution at any sufficiently distant, future time. Climate scientists working in dynamical systems theory are aware that no such guarantee exists and have proposed that the climate of a system that does not have a well-defined distribution at a sufficiently distant, future time should be identified with the system's pullback attractor (Chekroun, Simonnet, & Ghil, 2011; Ghil, 2015) or with its so-called snapshot attractor (Drótos, Bódai, & Tél, 2015). In any

case, when climate scientists do find it useful, e.g., for reasons of mathematical tractability, to use an infinite distribution to characterize a climate state, they are often careful to justify the appropriateness of this characterization in empirical and theoretical terms (see, e.g., Palmer, 1999).

Another potential issue Werndl raises is whether climate states should be characterized in terms of distributions under constant or varying external conditions (such as the solar energy flux). As Werndl notes, climate scientists sometimes work with characterisations according to which external conditions are constant (see, e.g., Lorenz, 1995). However, since it is well known that external conditions in reality vary somewhat over even very short time periods, as well as over the longer time periods for which climate scientists typically seek to characterize climate states, it seems better to think of this not as an issue of how to define climate states, but rather as an issue of how to adequately model them in a given study; in some cases, representing them as distributions emerging under constant external conditions can be justified, given the aims of the study, though this is surely an idealization for real-world time periods of interest.

4. Climate change and climate sensitivity

Climate change is, according to the IPCC, a persistent change in the distribution of climate (IPCC, 2014, p. 120). In contexts where a dynamical systems perspective on climate change is adopted, climate change is sometimes taken to be the change in the climate system attractor that results from some external forcing (see, e.g., Palmer, 1999). While statistical/mathematical definitions of climate change are most prominent, definitions that focus on material aspects are also available. Thus, Pielke (2010) writes: "Climate Change is any multi-decadal or longer alteration in one or more physical, chemical and/or biological components of the climate system."

The central issues relating to the notion of climate change are intimately tied to those relating to the notion of a climate state; once we know how to think about climate states, how to think about climate change follows (at least, it follows leaving aside important technicalities about how to characterize the change quantitatively). Nevertheless, one issue that the notion of climate change itself focuses our attention on is which quantities' distributions should be used in characterizing climate states and climate change. Standard characterizations of both are in terms of mean surface temperature, precipitation patterns and other quantities related to weather. Pielke (2003; 2008), however, proposes that changes in ocean heat content are a better indication of the actual heat accumulating in the climate system in response to radiative forcing as well as a better indication of future warming of the system.[3] He, accordingly, proposes that accumulated ocean heat content rather than changes in global mean surface temperature should be the primary measure of the specific aspect of climate change that is global warming (see also Victor & Kennel, 2014). One drawback of focusing on ocean heat content as a measure of global warming, however, is that this quantity – because it concerns conditions throughout the ocean – is even further removed than global mean surface temperature from the sorts of local changes in ocean and atmospheric conditions that matter to people and that thereby motivate policy action (Rahmstorf, 2014); how, if at all, a given increase in ocean heat content affects us at a given time depends on how the increased heat is distributed in the ocean and, in particular, on the extent to which it affects ocean surface temperatures. Another significant drawback is that ocean heat content is quite difficult to measure (Rahmstorf, 2014). The issue here seems to reflect a tension between the normative (which way of characterizing climate change best reflects our concerns) and the empirical (changes in global mean surface air temperature are not an accurate reflection of changes in the climate system's total heat storage).

Closely related to the notion of climate change are notions of climate sensitivity, which provide standardized ways of quantifying the response of the climate system to a change in forcing. The most widely used notion of climate sensitivity is that of equilibrium climate sensitivity. This notion is informally defined as the global mean surface temperature change that results from a doubling of atmospheric CO_2 after the fast-acting feedback processes within the ocean-atmosphere system, e.g., the water-vapour feedback and cloud feedback, have reached equilibrium (Charney, 1979; IPCC, 2014, p. 1761).[4] More formally, the notion of equilibrium climate sensitivity can be defined using what is called the climate sensitivity parameter, here represented by 'S'. S is given by $\frac{\Delta T}{\Delta R}$, where ΔT is the difference in global mean surface temperature between two statistical steady states, i.e., two states that have unchanging mean surface temperature distributions, and ΔR is the radiative forcing associated with the cause of the transition between the states, e.g., with certain changes in atmospheric CO_2 or CH_4. Equilibrium climate sensitivity is then defined as the temperature change $S \times \Delta R_{2\times CO_2}$, where $\Delta R_{2\times CO_2}$ is the change in forcing due to a doubling in CO_2 levels (von der Heydt et al., 2016). The more formal notion of equilibrium climate sensitivity is thus defined with respect to statistical steady states rather than equilibrium. Moreover, the formal definition assumes that S does not depend on the type of forcing, something that facilitates estimating the joint effects of different kinds of forcings. Both assumptions are made in order to make equilibrium climate sensitivity something that is quantifiable and useful in practice (Sherwood et al., 2015).[5]

Even so, the notion of equilibrium climate sensitivity remains insufficiently general in ways that make it ill-suited to some of the central inferential tasks that motivate thinking about the sensitivity of the climate system in the first place. First, the notion is applicable when Earth's mean surface temperature is in a statistical steady state; yet this condition is not generally met in reality. This complicates both estimating equilibrium climate sensitivity from data and using such estimates to make inferences about future changes that might occur in the actual climate system. For example, to try to infer climate sensitivity from palaeo-data, we might assume that data are being gathered from a time when the effects of fast feedback processes are no longer giving rise to a net top-of-the-atmosphere radiative imbalance, and thus are not affecting the global mean surface temperature distribution. But we still must try to correct for the effects of any slow feedbacks, e.g., of ocean heat uptake, which may not yet have equilibrated (von der Heydt et al., 2016). While this issue is partly a matter of limited knowledge of what the slow feedbacks are, it is also partly that the notion of

[3] Radiative forcing is, roughly, the change in net radiative flux at the tropopause that results from a change in some external condition or factor. We return to this concept in section 5.

[4] A climate feedback is a process internal to the climate system that either amplifies or dampens the initial effect of external forcings or internal variability (USNRC, 2005, p. 13).

[5] Because of the significant computational expense involved in running complex climate models until they are in equilibrium following a change in forcing, equilibrium climate sensitivity is often estimated from such models' transient climate response (IPCC, 2014, p. 1761). The transient climate response is defined as the increase in temperature at the time of CO_2 doubling after a 1% per-year increase in CO_2 concentrations in a climate model simulation (IPCC, 2014, p. 1761). Several of the problems we will raise for the notion of equilibrium climate sensitivity also arise for the notion of a transient climate response (see, e.g., Gregory, Andrews, & Good, 2015).

equilibrium climate sensitivity, by its very nature, provides no guidance as to how to take non-equilibrated feedbacks into account.

A second way in which the standard notion is insufficiently general is that it does not recognize that global temperature change, including the equilibrium response, can depend on the nature and spatial distribution of external forcings as well as on the state of Earth's climate system (von der Heydt et al., 2016). This kind of dependence might become important when, for example, trying to learn from palaeoclimate data, which often come from periods in which the climate system is thought to have been in a substantially different state from its current one (Skinner, 2012).

This same lack of generality also complicates learning about the 'climates' of complex climate models (CCMs), that is, of atmosphere-ocean general circulation models and Earth system models. Energy balance climate models, as well as other simple climate models, can be designed – partly by tuning their parameters – to emulate the simulation output of CCMs. As a result, simple models can be used to try to predict the output of CCMs under forcing settings to which the CCMs have, due to computational cost or structural inflexibility, never been subject. The equilibrium climate sensitivity parameter is an important tuned parameter in many simple models used to emulate CCMs. But it fails to account for the fact that climate sensitivity in CCMs is time-dependent and, indeed, is so partly because, as in the real climate system, it depends on the spatial distribution of external forcing (Senior & Mitchell, 2000, Meinshausen, Raper, & Wigley, 2011, Knutti & Rugenstein, 2017).

The limited usefulness of the equilibrium climate sensitivity parameter in emulation is being addressed in a number of ways. Most directly, simple model emulation of CCMs has been improved by observing the time-dependence of the climate response to forcing in CCM simulations and, on this basis, introducing time-dependence into the climate sensitivity parameters of simple models (Meinshausen et al., 2011). In addition, the structure of emulators has been modified in order to try to accommodate the time-dependence of the climate response in CCM simulations (Meinshausen et al., 2011). Knutti and Rugenstein (2017), however, note that studies grounded in CCMs have not managed to narrow the uncertainty about the current equilibrium climate sensitivity of the Earth system; the IPCC (Collins et al., 2013) assesses the likely range to be 1.5 °C - 4.5 °C, which is the same range as the one provided by the Charney Report in 1979 (Charney, 1979). In addition, CCMs are known to be subject to shared biases in their representation of feedbacks and thus in their estimates of equilibrium climate sensitivity (Knutti & Rugenstein, 2017). Consequently, it is worthwhile to consider other approaches to addressing problems with the notion of equilibrium climate sensitivity as well (von der Heydt et al., 2016; Knutti & Rugenstein, 2017).

Notably, there have been efforts in the paleoclimate context to generalize the notion of equilibrium climate sensitivity, motivated in part by the goal of improving palaeo-data based estimates of current climate sensitivity (von der Heydt et al., 2016). These generalized notions are often informed by considerations from dynamical systems theory. Dijkstra and Viebahn (2015), for example, define the conditional climate sensitivity parameter $S(\delta, t_e)$ of a background or base climate state, $\overline{T}$, as follows:

$$S(\delta, t_e) = \frac{\Delta T(\delta, t_e)}{\Delta R(\delta, t_e)}$$

Here, $\Delta T(\delta, t_e) = |T(t_e) - \overline{T}|$ is the maximum temperature difference that can occur during the period t_e, given the constraint $|T(0) - \overline{T}| < \delta$, that is, the constraint that the initial temperature perturbation is sufficiently small. $\Delta R(\delta, t_e)$ is the change in radiative forcing over t_e. Ghil (2015) provides a notion of climate sensitivity that extends to the non-equilibrium case and captures ways in which climate might respond to forcing that cannot be represented by a single scalar quantity.

These efforts focus on providing a sufficiently general mathematical characterization of climate sensitivity; they allow for additional ways in which the climate's response to radiative forcing might depend on the state of the climate system. They do not tell us, however, how to characterize this state. Yet, further developing the notion of a climate state by incorporating information about the drivers of climate variability (as discussed in Section 3) may facilitate the application of the more general ways of thinking about climate sensitivity. Incorporating such information might be helpful, for example, when attempting to draw conclusions about current climate sensitivity from palaeo-data based estimates of the (non-equilibrium) climate sensitivity of past climate states. In addition, such information might inform the use and development of simple dynamical models – i.e., simple models that represent the causal dependencies of key factors in the climate system – in order to learn about climate sensitivity. These simple models become particularly important in a context in which we aim, or need, to supplement studies that employ CCMs.[6] Information about drivers of variability might aid not only the selection of variables and processes to represent in the simple models but also, relatedly, judgments about when such models are sufficiently realistic to be of use in learning about climate sensitivity. Ideally, then, drivers of variability (and other physical information used to characterize climate states) will be described in terms of physical quantities and structures that are not too difficult to represent in dynamical climate models, including simple models. Both the potential usefulness of developing notions of climate states that facilitate learning about climate sensitivity from palaeo-data and the potential usefulness of developing such notions in a way that facilitates the use of simple dynamical models in learning about climate sensitivity suggest that there may be some benefit to developing notions of climate states and climate sensitivity in tandem.

Finally, the focus on equilibrium climate sensitivity, and thus on global mean surface temperature, as a proxy for climate change itself deserves some consideration. Equilibrium climate sensitivity is a relatively easy to calculate and grasp proxy quantity for climate change in all its complexity. Whether it is the best proxy for these purposes is far from clear, in part for the reasons discussed above. Further questions about its suitability arise in light of the fact that climate change can arise independently of any global radiative imbalance at the tropopause and thus independently of radiative forcing as it is standardly understood. Anthropogenic climate change that can occur partly independently of a tropopause radiative imbalance, and thus that cannot be captured by the standard notion of forcing, includes climate change due to the radiative effects of absorbing aerosols, climate change due to perturbations of ozone in the upper troposphere and lower stratosphere, and climate change due to the radiative and non-radiative effects of changes in land-use, e.g. deforestation and urbanization (USNRC, 2005, p. 86, Sherwood et al., 2015). We return to this issue in the final part of the next section.

[6] Simple dynamical models are, for example, used to illustrate the time-dependence of climate sensitivity (e.g., von der Heydt & Ashwin, 2016) and to learn about the sensitivity of the climate system on geological time scales (e.g., Berger and Loutre 2002).

5. Internal variability and radiative forcing

According to the IPCC, climate variability refers to variations in the mean state and/or other statistics of climate system conditions on all spatial and temporal scales beyond that of individual weather events (IPCC, 2014, p. 121). Internal variability is understood to be a species of climate variability: it is variability in climate system conditions due to natural processes within the system. Alternatively, climate variability may be due to natural or anthropogenic external forcing, in which case it is "external variability" (IPCC, 2014). Some core methodologies of climate science assume that internal and external variability are distinct, additive components of total climate variability (Bindoff et al., 2013, p.874, Knutti & Rugenstein, 2017, p. 4, Parker, 2010a).[7] For example, standard 'fingerprint' methodologies for attributing recent climate change to particular causes ask whether observed variability is consistent with the sum of estimated contributions from different external forcings (including rising greenhouse gas concentrations) and internal variability; estimates of the latter are often obtained by running long simulations in which external conditions are held constant (e.g. at pre-industrial levels) (Bindoff et al., 2013). In the context of these methods, internal variability is variability that would occur in the absence of external forcings.

At least two issues arise in connection with this way of thinking about internal variability. First, what counts as 'internal' versus 'external' obviously depends on how the boundaries of Earth's climate system are defined; as noted in Section 2, this is not a straightforward matter. Second, it is quite plausible that, even on relatively short time scales, external forcing sometimes changes the operation of natural internal processes – changing, for instance, the magnitude and/or frequency of internal oscillations like the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation (e.g. Knudsen, Jacobsen, Seidenkrantz, & Olsen, 2014). In such situations, are the changes in climate system conditions stemming from the changes in natural internal processes – such as more extreme droughts in some regions – part of a new pattern of internal variability, one associated with the post-forcing external conditions? Or are they part of external (i.e., forced) variability?

A problem with the first option is that it seems to render invisible the fact that the changes in natural internal processes – which in turn might be responsible for changes in extreme weather with harmful consequences – were caused by changes in external forcing. Indeed, it seems to leave us unable to attribute those additional harmful consequences to the relevant external forcing, such as rising greenhouse gas concentrations; they are part of (unforced) internal variability instead. In part for this reason, the second option seems more attractive. Moreover, some standard attribution methodologies, as outlined above, also would characterize such changes in extreme weather as external variability, in accordance with the second option.

However, the second option raises challenges of its own. Taken at face value, it seems to lead to the conclusion that all climate variability is external variability, insofar as the operation of natural internal processes at any given time has been shaped in a host of ways by external forcing that occurred earlier in Earth's history. One way to avoid this conclusion is to understand internal variability in the way implied by current model-based methods for estimating it: the internal variability associated with time period T is the variability that would be expected to occur in that period if external conditions during T remained as they were at the start of T (i.e., at some fixed level). Yet there are odd consequences lurking here too. Note that, for time periods in which external forcing is significantly changing the operation of natural internal processes, this way of thinking about internal variability makes it a counterfactual property of the climate system, a property that the climate system would have had if external forcing had made little difference to the operation of natural internal processes. Yet it seems odd to analyze actual climate variability as having a counterfactual component; insofar as internal variability is a species of actual climate variability, it seems it should be an actual property of the climate system during T, closely tied to the ways in which natural internal processes are in fact operating in T. At present, it is unclear whether current ways of thinking about internal variability (and, more broadly, about climate variability) can give a satisfactory analysis of situations in which external forcing substantially changes the operation of natural internal processes.

With regard to radiative forcing, the IPCC says that "[t]he strength of drivers is quantified as Radiative Forcing (RF) in units watts per square meter (W/m^2) as in previous IPCC assessments. RF is the change in energy flux caused by a driver and is calculated at the tropopause or at the top of the atmosphere" (2014, p. 126). If all tropospheric/top-of-the-atmosphere properties are held fixed at their unperturbed values, the radiative forcing is called the *instantaneous* radiative forcing. In the recent literature, however, radiative forcing is usually identified with the *adjusted* radiative forcing, that is, with the change in the net radiative flux at the tropopause once the stratosphere has returned to radiative equilibrium (USNRC, 2005, p. 17).

The above IPCC characterization of radiative forcing is not explicit about whether the drivers of such forcing must be external; in USNRC (2005) and some IPCC publications, this is assumed (see, e.g., the glossary used by the IPCC Data Distribution Centre, http://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html). If radiative forcing is understood to be external, the internal/external issue arises again. Further, as we saw in section 4, some processes that give rise to climate change, including changes in land use, are not associated with an energy imbalance at the tropopause. These processes – which seem to qualify as 'forcings' of some sort insofar as they can produce systematic and sustained changes in climate system conditions and are often thought of as 'external'– cannot be straightforwardly represented using standard notions such as equilibrium climate sensitivity and thus cannot have their contributions to climate change taken into account in the usual way. Thus, there seems to be a need for a less limited way of thinking about, and modelling, 'forcing' of the climate system (USNRC, 2005, Ch. 4, Sherwood et al., 2015). One approach would be to consider the total radiative forcing due to radiative tropopause imbalances and surface radiative forcing; the regional structure of radiative forcing, however, also needs to be taken into account, since this can affect which changes in climate are predicted to occur, and how to do this is largely unsettled.

6. Concluding remarks

We have identified a number of outstanding issues in the theoretical foundations of climate science. These include: how to draw the boundaries of the climate system; whether to pursue fully reductive notions of Earth's climate system and its states; whether climate states should be characterized statistically or in a combined physical-statistical way; which quantities (e.g. changes in global

[7] Not all attribution methods assume this. For instance, probabilistic event attribution – which aims to quantify the extent to which anthropogenic forcing has increased the probability of occurrence of a particular extreme weather or climate event – compares the estimated probability of occurrence of the event in the presence and absence of anthropogenic forcing (see Stott et al., 2013 for a review); these probabilities are often estimated by comparing simulations that include the anthropogenic forcing to simulations that exclude them, without assuming that there are separable and additive contributions from external forcing and internal variability to the estimated change in probability.

mean surface air temperature or ocean heat content) should be used in characterizing climate change; how to broaden notions of climate sensitivity in order to account for state-dependence and for spatial patterns of forcings; whether current ways of thinking about internal variability can accommodate situations in which external forcing substantially changes the operation of natural internal processes; and how to broaden the notion of forcing to accommodate processes that cause climate change but do not involve an energy imbalance at the tropopause. Along the way, we noted a number of connections among these issues. In particular, the issue of how to draw the boundaries of the climate system (and thus how to determine what is internal/external to the system) resurfaced a number of times, as did the question of how to characterize climate states.

Climate science has already begun to respond to some of these issues. For example, as we noted, more flexible notions of climate sensitivity have been developed in light of the limitations of the notion of equilibrium climate sensitivity. However, the use of these more flexible notions can bring its own challenges. For instance, in order to actually apply notions of climate sensitivity that account for state-dependence, one must come to some conclusion about what constitutes a climate state. In discussing the latter, we called attention to some advantages of a recent proposal to incorporate into the characterization of climate states information about physical drivers of conditions, rather than just statistical descriptions of those conditions. At the same time, we noted that, if such physical-statistical notions are to facilitate the application of generalized notions of climate sensitivity, it will be useful for information about physical drivers to be expressed in terms that can be represented by the variables and structures of dynamical climate models (which are used as aids in learning about climate sensitivity). These examples illustrate not only that it may be beneficial to address some issues in tandem, rather than individually, but also that progress in addressing issues in the theoretical foundations of climate science might often be made without abandoning existing notions entirely, but rather by supplementing or generalizing them.

We think that philosophers of science also could contribute when it comes to issues in the theoretical foundations of climate science. Most obviously, they might contribute by helping to articulate, in a clear and careful way, what the issues are. We have tried to do this in a preliminary way for the issues outline above, but for each there is room for significantly more work to be done. Philosophers might also propose ways forward in addressing some of these issues, as we have begun to, and even contribute to realizing these proposals, perhaps in collaboration with climate scientists. We think that it would be worthwhile to do so. Addressing issues like those that we have discussed can facilitate the development of clearer and more coherent ways of thinking about climate phenomena. Moreover, it can help climate science to become better equipped to tackle important explanatory and predictive tasks, including those related to global and regional climate change.

Acknowledgment

Thanks to the paper's reviewers for their helpful comments.

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